Challenges and prospects for dynamical cores of oceanic models across all scales

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COMMODORE — Community for the numerical modeling of the global, regional and coastal ocean

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Context: the ocean model developers community has had the tendency to be split depending on target applications (global vs coastal) and on the type of horizontal grids (structured vs unstructured)

FIRST COMMODORE WORKSHOP: COMMUNITY FOR THE NUMERICAL MODELING OF THE GLOBAL, REGIONAL, AND COASTAL OCEAN

WHAT: A total of 47 participants from 9 countries representing 15 different oceanic numerical models met to review our current understanding of future challenges in the design of oceanic dynamical cores.

WHEN: 17–19 September 2018

WHERE: Paris, France

1 - Major differences compared to atmospheric modeling

	Atmosphere	Ocean
Horizontal velocities U	$10\ \mathrm{m\,s^{-1}}$	$0.1\ \mathrm{m\,s^{-1}}$
Sound speed c_s	$\sim 340\ \mathrm{m\,s^{-1}}$	$\sim 1500\ \mathrm{m\,s^{-1}}$
External gravity waves c_0	$\sim \mathbf{300}\ \mathrm{m\,s^{-1}}$	$\sim \mathbf{100}\ \mathrm{m\,s^{-1}}$
Internal gravity waves c_1	$\sim \mathbf{100}\ \mathrm{m\,s^{-1}}$	$\sim \mathbf{1}\ \mathrm{m\,s^{-1}}$
First deformation radius	O(100 km)	O(10 km)

- **Density variations are quite small compared to the mean density**

  $\Longrightarrow$ Boussinesq approximation is valid ($\rightarrow$ no acoustic modes)
- **Validity of hydrostatic balance ($\delta^2 \mathrm{Fr}^2 \ll 1$)** : in the ocean the hydrostatic balance is violated approximately for $L < 1$ km and weak stratification

  $\Longrightarrow$ Oceanic non-hydrostatic models are at an early development stage
- **Stiffness ($c_0 \gg c_1$)**: fast modes are meteorologically important (i.e. accuracy matters) and propagate horizontally

  $\Longrightarrow$ Split-explicit treatment of 2D barotropic mode (+ consistency enforcement)
- Away from boundary layers, **tracers are stirred and mixed preferentially along isopycnal surfaces** : $\kappa_{\mathrm{dia}} \approx 10^{-5}\ \mathrm{m^2\,s^{-1}}$ (e.g. Ledwell et al., 1993); $\kappa_{\mathrm{iso}} \approx 10^{3}\ \mathrm{m^2\,s^{-1}}$ (for $L_x \approx 100$ km)

  $\Longrightarrow$ Strong constraint on the choice of vert. coord. & tracer advection/remapping schemes
- **Complex geometry (but no "Pole problem")**

  $\Longrightarrow$ Computational domain is bounded with irregular boundaries
- **Vacuum states (wetting and drying)**

  $\Longrightarrow$ Volume-conserving treatment of dry states and non-negativity of water heights

2 - Overview of equations and associated modeling assumptions

- **Geometric assumptions**
  - spherical geoid, traditional shallow-fluid
  - fixed bathymetry ($-H(x,y) \le z \le \eta(x,y,t)$)
- **Boussinesq**
  - *in-situ* density $\rho \rightarrow \rho_0$ except when associated with the gravitational term
- **Hydrostatic**
- **Thermodynamically consistent description of seawater** (Gibbs function)
  - Potential temperature θ is replaced by the conservative temperature $\Theta = h_0/c_p^0$.
- **Mode splitting**: fast surface gravity waves are integrated separately (depth independent barotropic mode approximation)

- Baroclinic (internal) mode

$$
\begin{cases}
\dfrac{D\mathbf{u}_h}{Dt} = -f\mathbf{k}\times\mathbf{u}_h - \dfrac{\boldsymbol{\nabla}_h p}{\rho_0} - g\boldsymbol{\nabla}_h\eta + \boldsymbol{\mathcal{F}}_{\mathrm{phys}} \\
\partial_z p = -g\rho \\
\boldsymbol{\nabla}\cdot\mathbf{u} = 0 \\
\dfrac{D\Theta}{Dt} = \dfrac{1}{\rho_0 C_p}\partial_z\mathcal{I} + \mathcal{F}_\Theta; \qquad \dfrac{DS_{\mathrm{A}}}{Dt} = \mathcal{F}_{S_{\mathrm{A}}} \\
\rho = \rho_{\mathrm{eos}}(\Theta, S_{\mathrm{A}}, z)
\end{cases}
$$

Kinematic surface boundary condition:

$$
w|_{z=\eta} = \partial_t\eta + \mathbf{u}_h(z=\eta)\cdot\boldsymbol{\nabla}_h\eta + (E-P)
$$

- Barotropic (external) mode ($\overline{\mathbf{u}} = \int_{-H}^{\eta}\mathbf{u}_h\,\mathrm{dz}$)

$$
\begin{cases}
\partial_t\eta = -\boldsymbol{\nabla}_h\cdot(D\overline{\mathbf{u}}) - (E-P) \\
\partial_t(D\overline{\mathbf{u}}) = -Df\mathbf{k}\times\overline{\mathbf{u}} - gD\boldsymbol{\nabla}_h\eta + D\boldsymbol{\mathcal{F}}_{3D\rightarrow 2D}
\end{cases}
$$

$\boldsymbol{\mathcal{F}}_{3D\rightarrow 2D}$: baroclinic-to-barotropic forcing.

3 - Brief overview of some existing dynamical cores

Acronym	website	Primary target application	horiz. grid	NH option
Croco	https://www.croco-ocean.org/	coastal	structured	Yes
FESOM	https://fesom.de/	global	unstructured	
GETM	https://getm.eu/	coastal	structured	Yes
Hycom	https://hycom.org/	global	structured	
ICON-O	https://www.mpimet.mpg.de/en/science/models/icon-esm/icon-o/	global	unstructured	
MITgcm	http://mitgcm.org/	global	structured	Yes
MOM6	https://github.com/NOAA-GFDL/MOM6-examples/wiki	global	structured	
MPAS-O	https://mpas-dev.github.io/	global	unstructured	
NEMO	https://www.nemo-ocean.eu/	global	structured	
Roms-Rutgers	https://www.myroms.org/	coastal	structured	
SCHISM	http://ccrm.vims.edu/schismweb/	coastal	unstructured	
Suntans	https://sourceforge.net/p/suntans/	coastal	unstructured	Yes
Symphonie	http://sirocco.obs-mip.fr/ocean-models/s-model/	coastal	structured	Yes
Thetis	http://thetisproject.org/	coastal	unstructured	

Table 1 : Summary of realistic oceanic models widely used by the research and operational community.

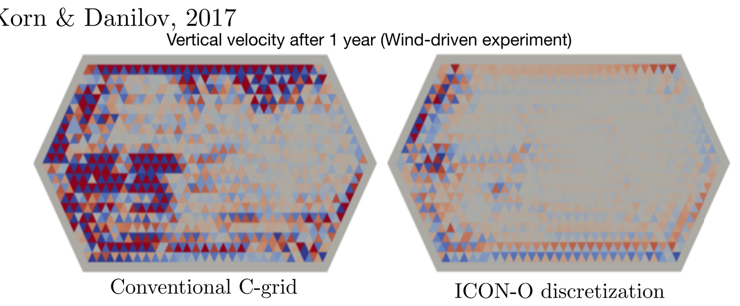
Model	Variables arrangement	Discretization technique	FE pair	Stabilization	Mesh	Mode splitting
FESOM	triangular B-grid	FV	-	-	Arbitrary	SPI
ICON-O	triangular C-grid	FE	modified $\mathrm{RT}_0 - P_0$	No	Orthogonal	SPI
MPAS-O	hexagonal C-grid	FV	-	-	Orthogonal	SPE
SCHISM	triangles or quads	FE	$P_1 - P_1^{\mathrm{NC}}$	No	Arbitrary	No
Thetis	triangles or quads	FE	$P_1^{\mathrm{DG}} - P_1^{\mathrm{DG}}$	Roe	Orthogonal	SPI

Table 2 : Overview of the main characteristics of some unstructured grid models.

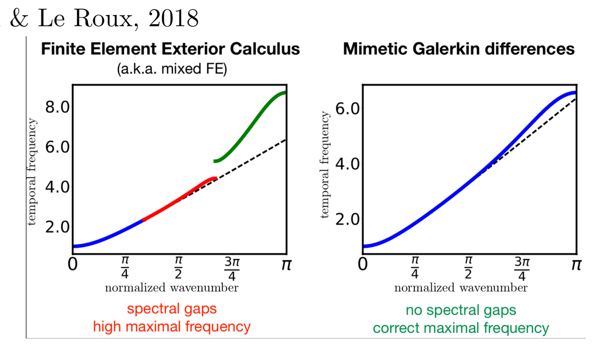
4 - Some prospects for oceanic dynamical cores

Control of spurious modes & spectral gaps (with FE methods)

Korn & Danilov, 2017

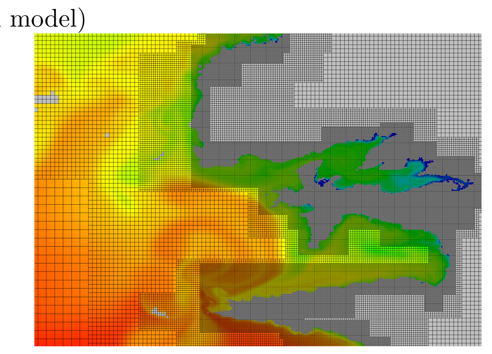


Eldred & Le Roux, 2018

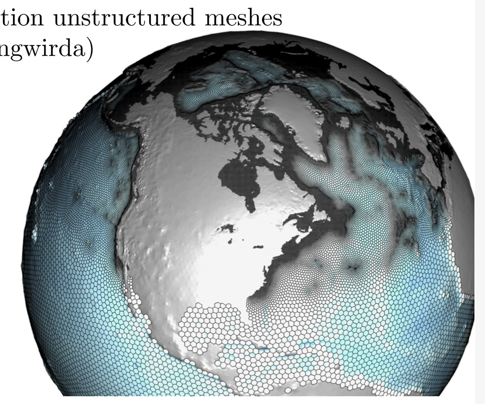


Multi-resolution strategies

Block structured mesh refinement (Croco Ocean model)

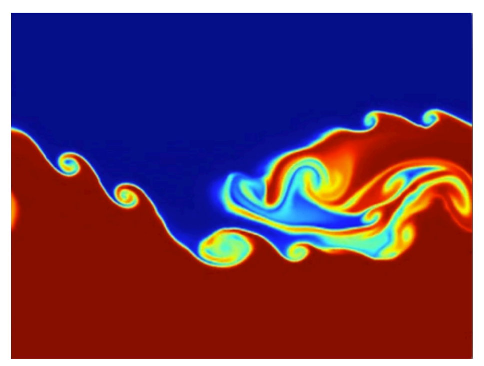


Variable resolution unstructured meshes (Courtesy of D. Engwirda)

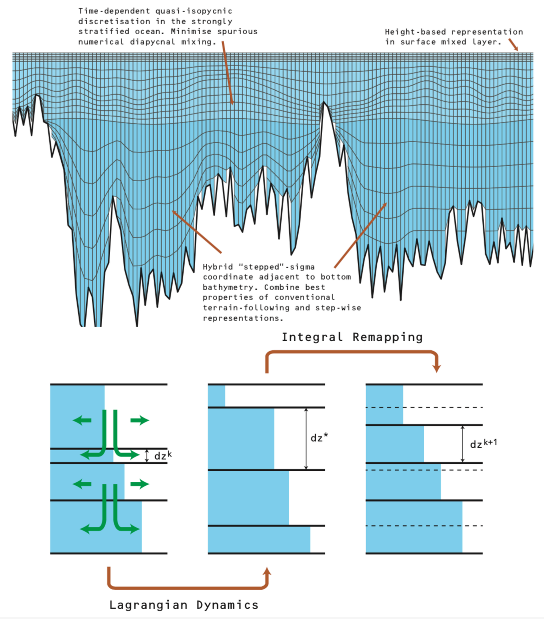


Inclusion of NH effects

1. Pseudo-compressible approach (Auclair et al., 2018) {Croco, SNH}
2. Incompressible pressure projection/correction approach {MITGcM, Suntans}
3. Artificial compressibility method (ACM) (Lee et al., 2006) {Symphonie}
4. Diagnostic approach for NH pressure (Klingbeil and Burchard, 2013) {GETM}



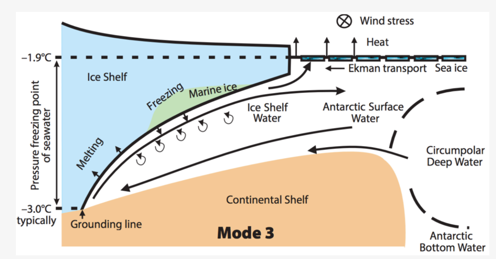
A.L.E. vertical coordinates



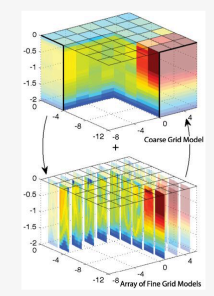
5 - Challenges

- **Challenges for unstructured meshes**: High-order methods and Local time-stepping
- **Energy consistency and resolved/unresolved scales coupling**
  - Discrete closing of the energy budget
  - Design of energy-conserving space and time discretizations
- **Control of energy, non-negativity and dry states for nonlinear scalar conservation laws**
- **Stable and consistent coupling with other Earth-system compartments**

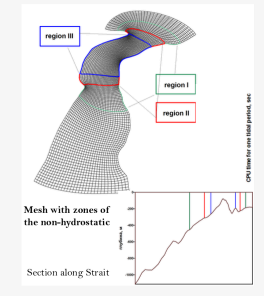
(e.g. interactions between ocean, sea ice and ice shelves)



- **Multi-resolution strategies with local adaptation of model equations**

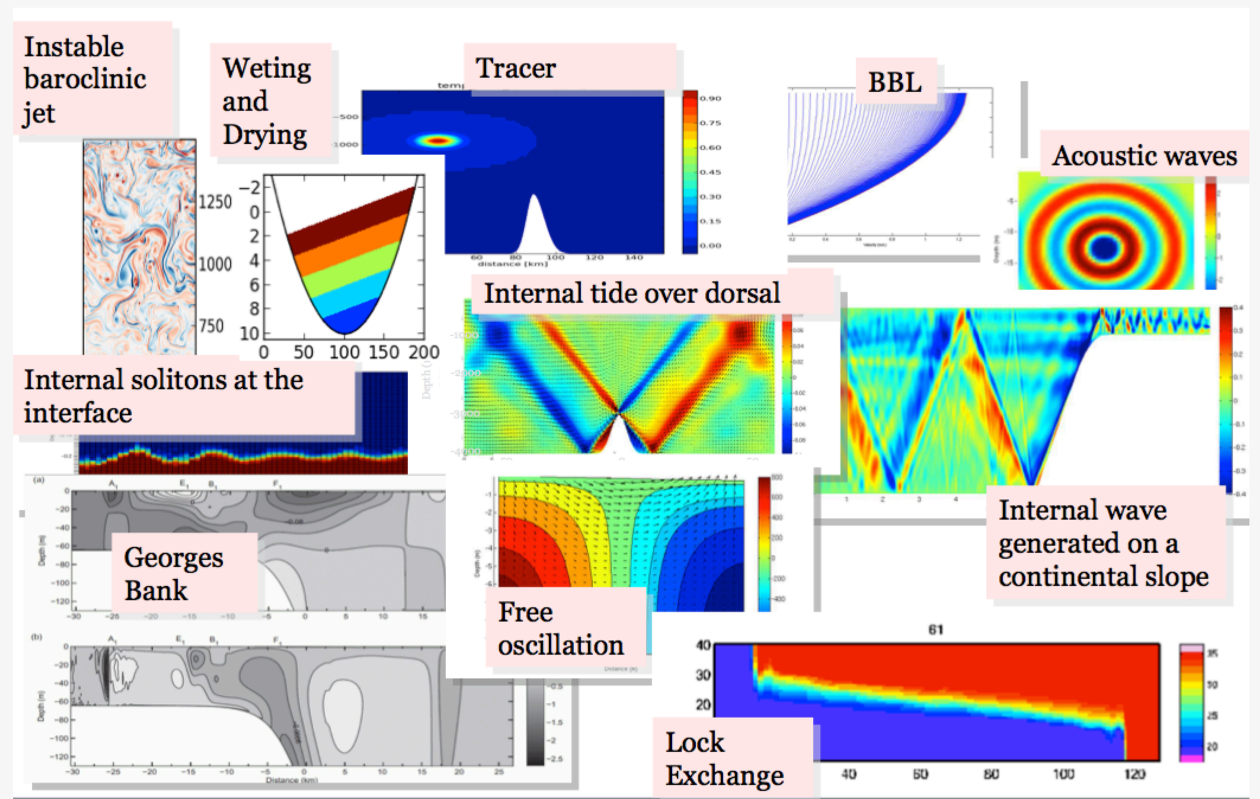


via super-parameterization (Campin et al., 2011)



via automatic selection of NH zones (Androsov et al.)

6 - Toward a "DCMIP-like" test-case suite



Any suggestion for semi-idealized testcases are welcome

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